Analysis of Geant4 Physics Processes for μ^- Capture At Rest

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The Geant4 processes for μ^- capture at rest are examined. The broad features appear to be correct, but some details are incorrect. The DIO e^- energy endpoint is OK, as are gamma cascades from Boron and Neon (compared to experiments). However proton emission appears to be too small by a factor of ~3, neutron emission appears to be too small by ~30%, and the ^{27}Al recoil nucleus is omitted in muMinusCaptureAtRest. In addition, charge, energy, and momentum are not conserved, but this is mostly related to the omission of the very slow nuclear recoil.

Background

This study was performed using G4beamline 2.03b, which is based on Geant4 9.3. The technique was to send a 0.1 MeV/c μ^- beam into a 1 micron Al foil and observe the secondaries emitted by the μ^- capture process. 100% of the incident μ^- stopped in the foil, and 100% of them were captured by an Al atom. The geometry was designed to minimize decay losses (0% achieved), and to minimize the impact of the aluminum disk on outgoing particles. 10,000 μ^- were used for each physics list, and 1 million events were used for the plots. The technique looks directly at the tracks created by the capture process, and thus does not depend on how secondaries might interact in the disk. Every physics list implemented in Geant4 9.3 was examined.

Physics Processes for mu- Capture in Atoms

As far as μ^- capture is concerned, the physics lists fall into the following categories:

- Physics lists that use muMinusCaptureAtRest:
  FTFP_BERT, FTFP_BERT_EMV, FTFP_BERT_TRV, FTF_BIC, LHEP, LHEP_EMV, QGSP_BERT, QGSP_BERT_EMV, QGSP_BERT_HP, QGSP_BERT_NOLEP, QGSP_BERT_TRV, QGSP_BIC, QGSP_BIC_EMY, QGSP_BIC_HP, QGSP_FTFP_BERT, QGSP_INCL_ABLA, QGS_BIC, LISAPhysicsList
- Physics lists that use CHIPSNuclearCaptureAtRest:
  CHIPS, QGSC_BERT, QGSC_CHIPS
- Physics lists that have no μ^- capture process at all:
  FTFP_BERT_EMX, LBE, MICEPhysicsList, QBBC, QBBC_XGG, QBBC_XGGSN, QGSP_BERT_EMX

Note, however, that while most physics lists use muMinusCaptureAtRest, the propagation of neutrons out of the target is dependent on the other aspects of the physics list, and only these can be expected to give good results for neutrons: QGSP_BERT_HP, QGSP_BIC_HP.

Table 1 gives a summary of the particles produced by the two μ^- capture processes, with their probabilities. Note that 100% of the incident μ^- stopped in the Al disk, and 100% of them were captured by an Al atom.

Table 1. Secondary Particles produced by μ^- Capture at Rest in an Al target.

Particle	muMinusCaptureAtRest	CHIPSnuclearCaptureAtRest
Al27	0.0%	39.4%
C12	0.0%	0.5%
C13	0.0%	0.0%
F18	0.0%	0.0%
F19	0.1%	0.0%
F20	0.2%	0.0%
F21	0.0%	0.0%
F22	0.0%	0.0%
He3	0.0%	0.0%
Mg23	0.0%	0.2%
Mg24	5.4%	15.7%
Mg25	13.8%	9.8%
Mg26	24.4%	12.9%
Mg27	7.4%	7.6%
N14	0.0%	0.0%
N15	0.0%	0.1%
N16	0.0%	0.0%
Na22	0.2%	0.0%
Na23	1.6%	2.7%
Na24	1.5%	0.6%
Na25	0.9%	0.1%
Na26	0.1%	0.0%
Ne20	0.8%	6.8%
Ne21	1.7%	1.1%
Ne22	2.4%	1.1%
Ne23	0.7%	0.1%
Ne24	0.0%	0.0%
O15	0.0%	0.0%
O16	0.0%	1.0%
O17	0.2%	0.1%
O18	0.1%	0.1%
O19	0.1%	0.0%
alpha	6.6%	13.1%
anti_nu_e	38.5%	39.4%
deuteron	2.0%	0.4%
e-	292.6%	39.4%
gamma	673.0%	0.0%
neutron	83.6%	119.7%
nu_mu	100.0%	100.0%
proton	1.9%	4.1%
triton	1.0%	0.1%

These processes combine decay in orbit (DIO) and nuclear capture. Presumably the 38.5%/39.4% of events with an anti_nu_e are DIOs, and the ones without are nuclear captures. That is consistent with the correct percentage for Al.

There are a number of questions/puzzles about Table 1:

muMinusCaptureAtRest

1. Why no Al27? – all decays in orbit should give this; is it omitted because it is so slow?
   All of the Al27 recoils in CHIPS have kinetic energies below 2 MeV, 90% are below 1 MeV. Setting the range cut to 0.0000000001mm does not make them appear. For elastic nuclear scattering this can be controlled by a Geant4 function G4HadronElastic::SetRecoilKinEnergyLimit(), which G4beamline does not use; it defaults to 100 keV, which explains why no elastic nuclear recoils are seen.

2. Why so many e-?
   Unknown; possibly/probably correct.

3. e- energy spectrum – check endpoint to see if it is truly decay in orbit, or merely free decay (cut on existence of anti_nu_e to remove nuclear captures).
   The endpoint looks correct (plot below); compare to μ^+ decays.

4. gamma energy spectrum – look for μ^- atomic cascade.
   Looks OK; plots below for Boron and Neon muonic atoms.

5. neutron – expected about 120%, got 83%.
   The Geant4 muMinusCaptureAtRest process does not include the high-energy component that both MARS and the MECO Monte Carlo have. A new G4beamline command, muminuscapturefix, has been written to generate this component (plots below).

6. proton – expected about 6%, got 2% (this is an important background to study).
   Unknown. Could be related to charge non-conservation.

7. Is charge conserved?
   Not in nuclear captures (e.g. $\mu^- + \text{AL27} \rightarrow \text{Mg26} + 8\ \text{gamma} + 4\ \text{e-} + \text{nu\_mu}$). Indeed there are often extraneous e-, even for DIO, so it is likely that the recoil nucleus is ionized (I cannot see its charge).

8. Are energy and momentum conserved?
   Probably not, given that AL27 is omitted. Difficult to check. Certainly the extra neutrons from muminuscapturefix do not satisfy momentum conservation. But of course there is a recoil nucleus with unknown momentum that could fix it up.

CHIPSnuclearCaptureAtRest

1. Look at energy spectrum of Al27 – how slow are these? Is it reasonable for muMinusCaptureAtRest to omit them?
   All have KE < 2 MeV; 90% have KE < 1 MeV. Omitting them is not likely to affect

much.

2. gamma – this cannot possibly be correct, because of the μ^- atomic cascade. Don't use this physics process.

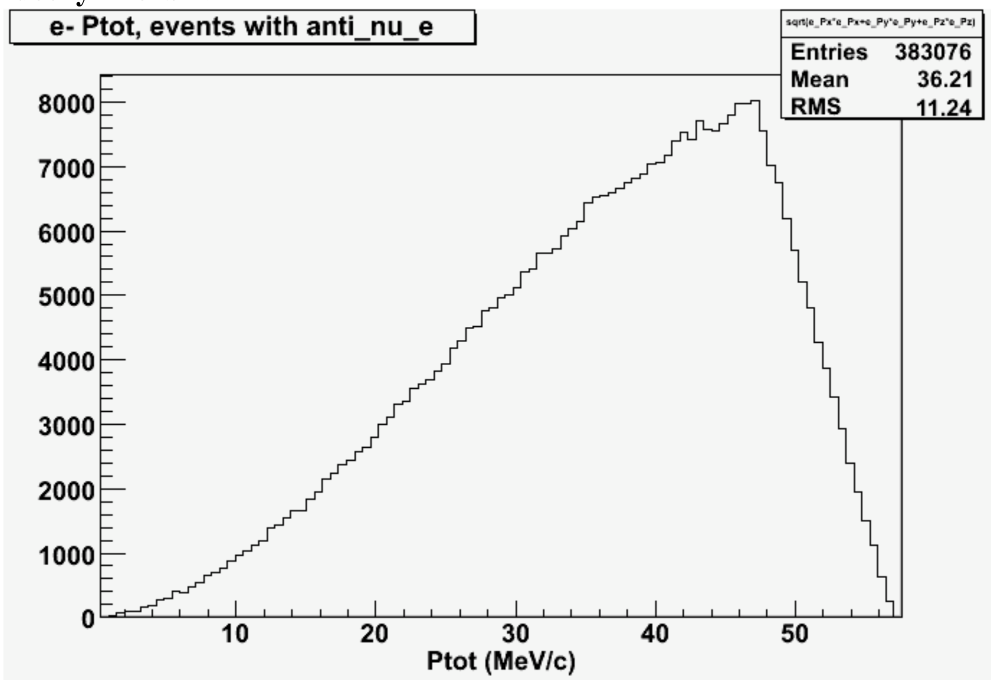
Note that the code for both of these processes is monolithic, limiting the ability to devote background runs specifically to DIO, to nuclear capture, etc.

Plots for muMinusCaptureAtRest

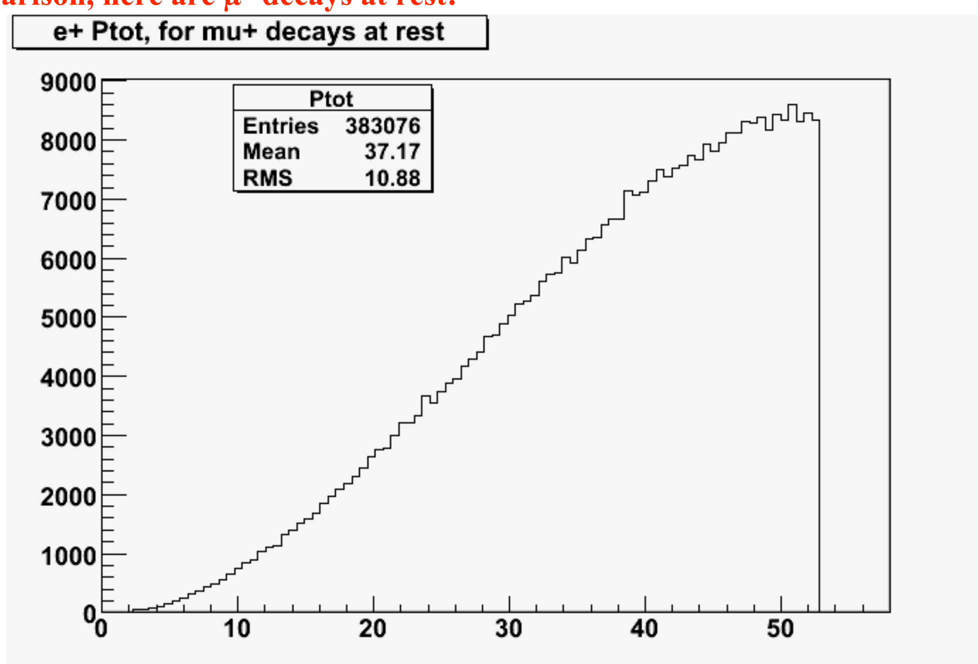
Plots are for 1 Million μ^- stopping in Al.

Electrons

These are decay in orbit:

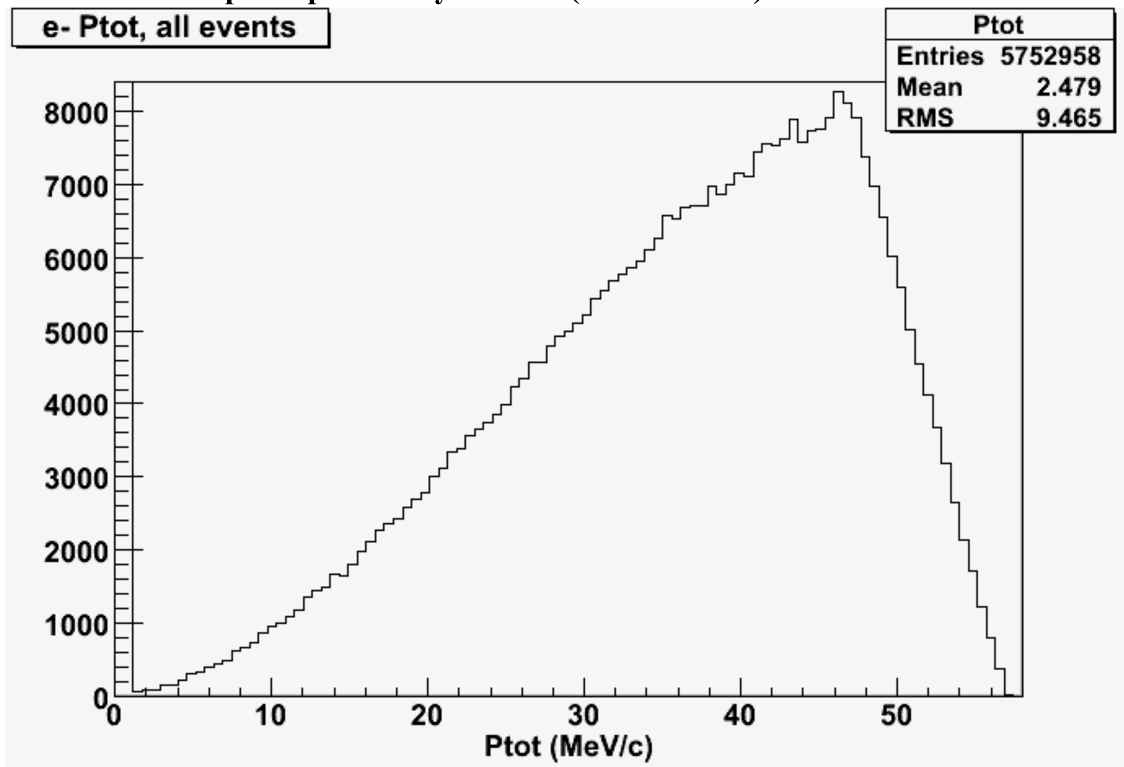


For comparison, here are μ^+ decays at rest:



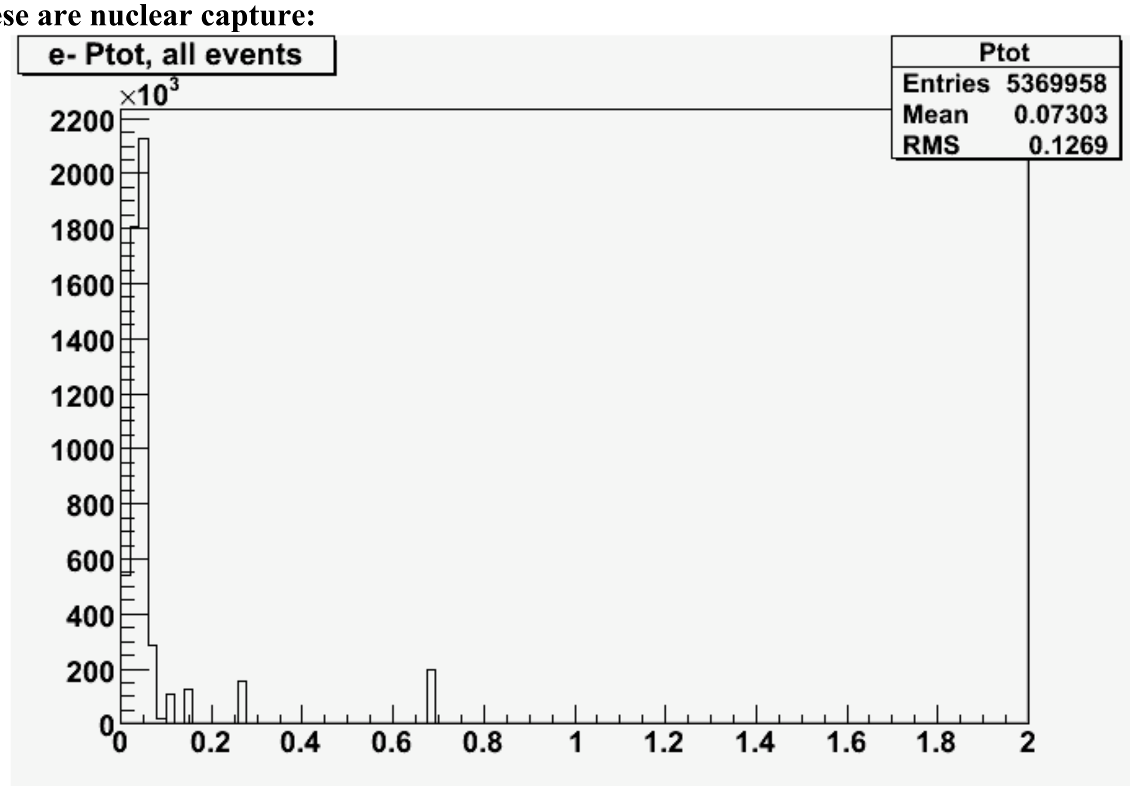
(These are μ^+ decays at rest inside the same Al disk, same # events as above.)

These are nuclear capture plus decay in orbit (i.e. all events):



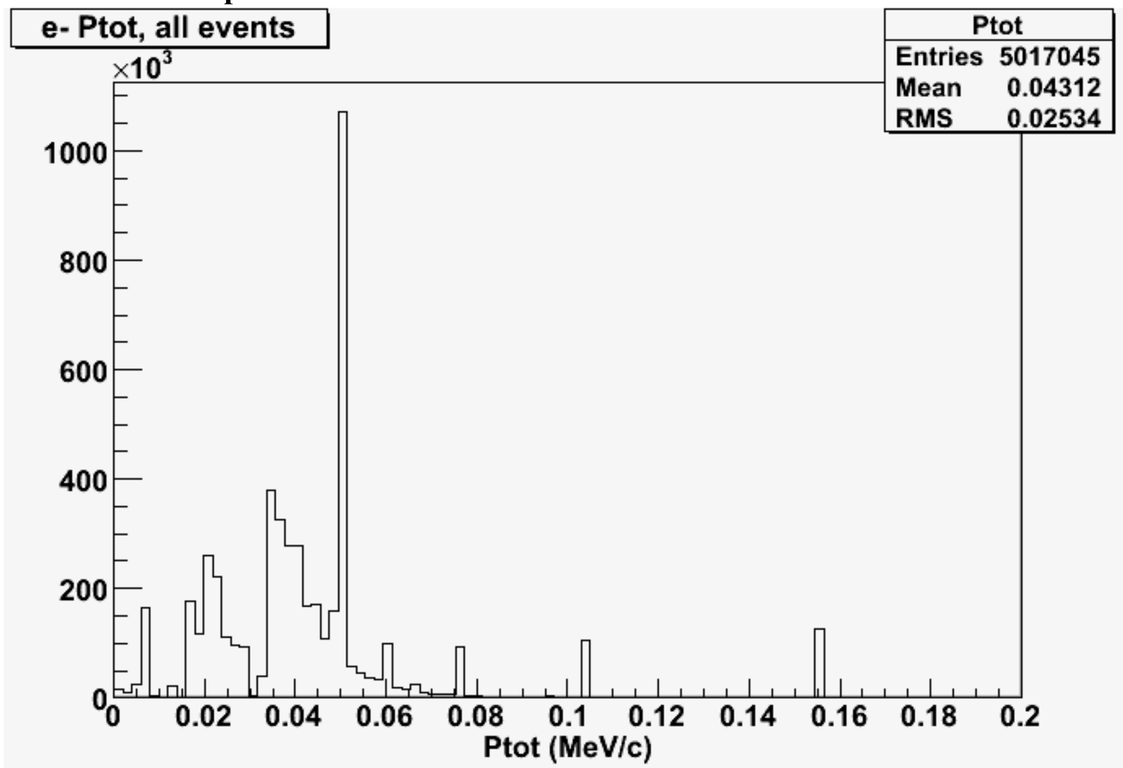
(Y scale greatly expanded to show the detail above 2 MeV/c; 94% of events are below 2 MeV/c)

These are nuclear capture:



X scale expanded to show detail below 2 MeV/c.

These are nuclear capture:

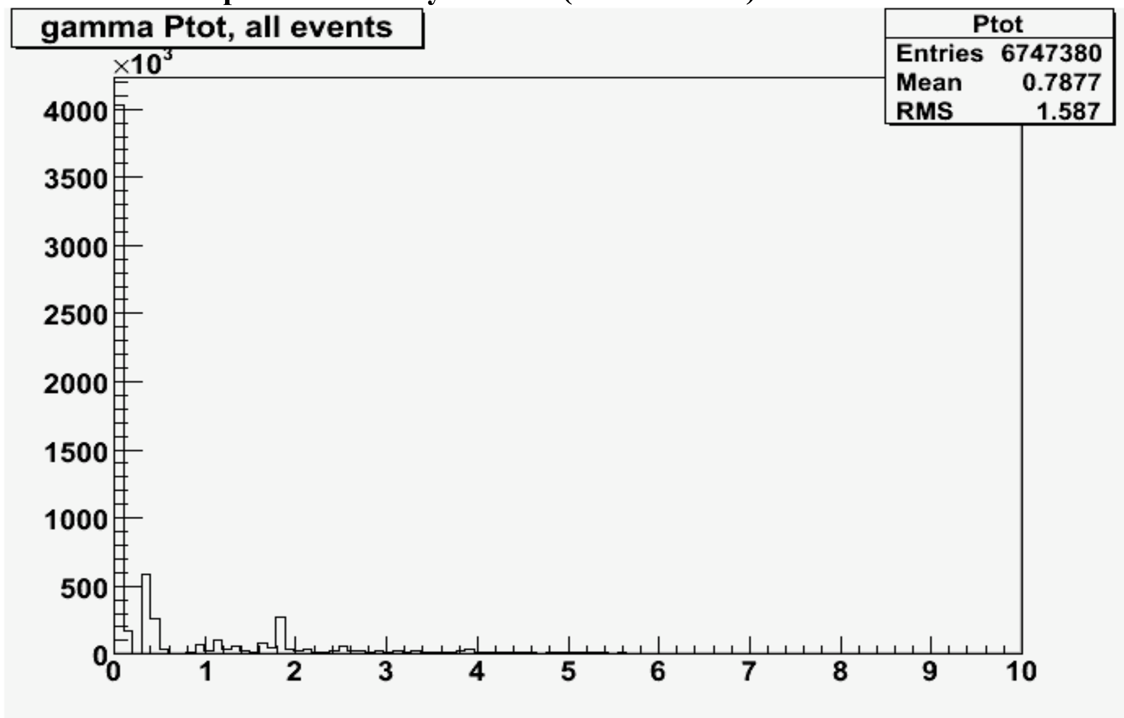


X scale expanded to show detail below 0.2 MeV/c.

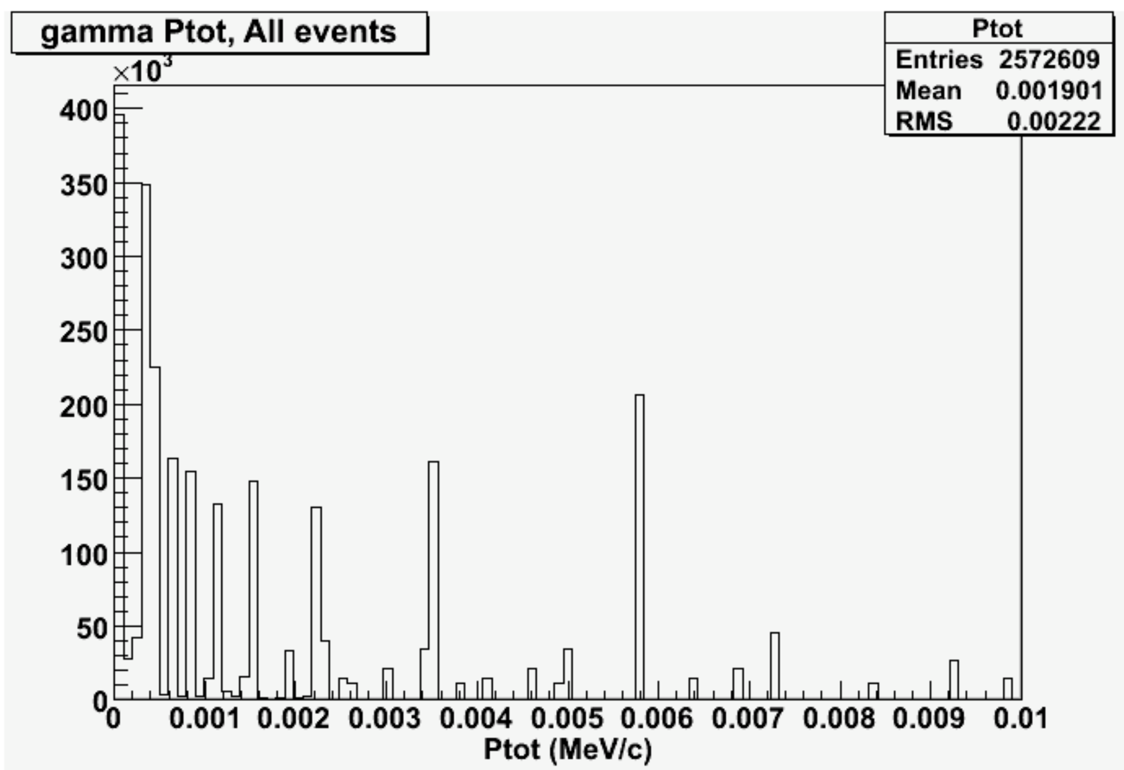
The origin of the spike at 0.05 MeV/c is unknown (K.E. = 2.4 keV).

Gammas

These are nuclear capture and decay in orbit (i.e. all events):



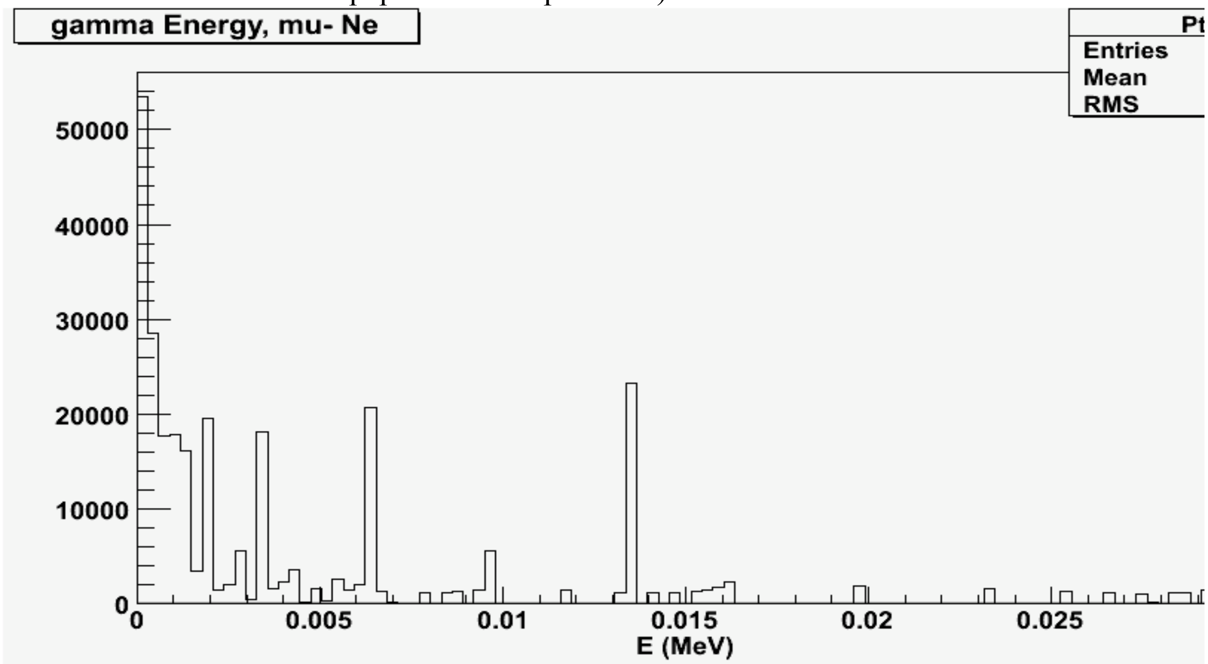
gammas (include all gammas, not just from μ^- atoms.)

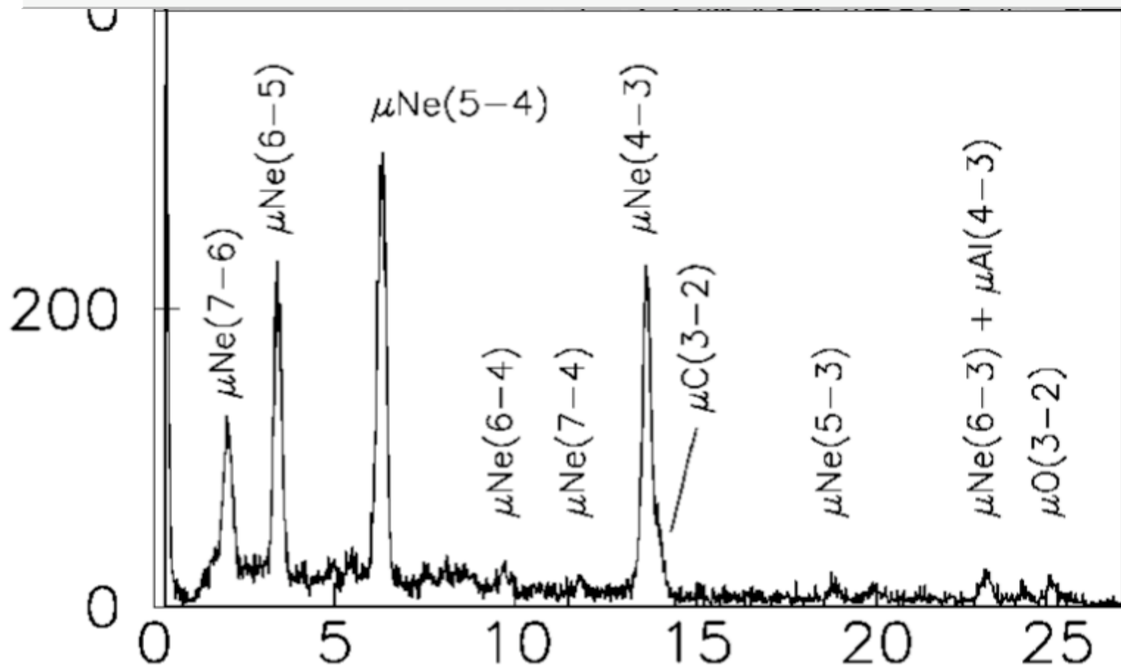


gammas (include all gammas, not just from μ^- atoms.); X scale expanded.

Muonic Atom Gamma Cascades

Energy of Gammas from μ⁻ Neon (muMinusCaptureAtRest, QGSP_BERT_HP)
(Use Neon because I found a paper with its spectrum.)

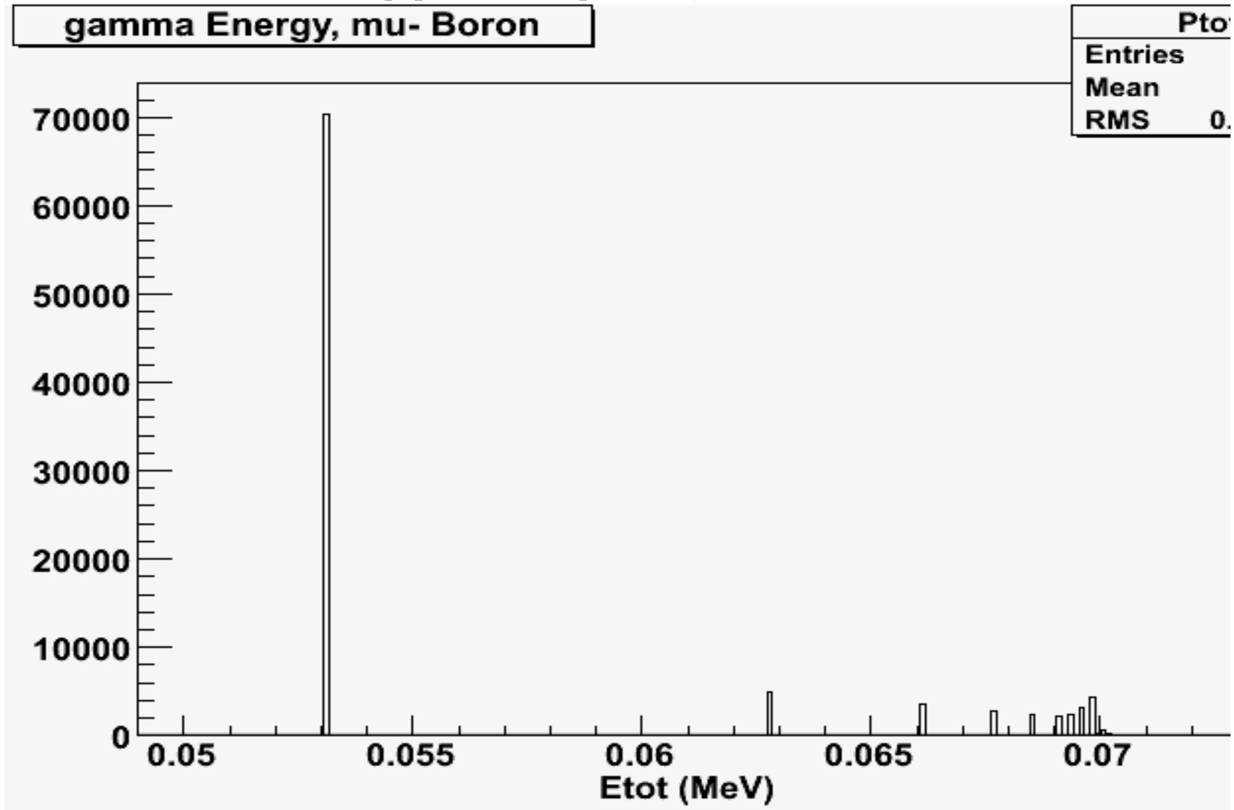


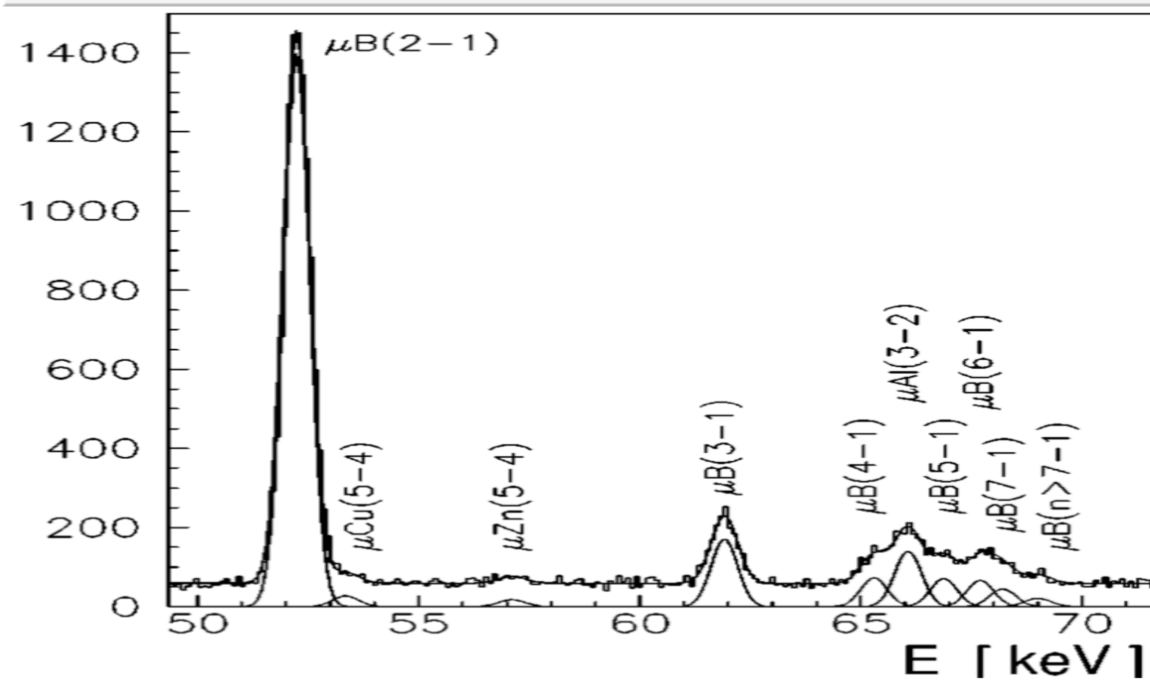


Experimental X-ray Spectrum for μ⁻ Neon, from Kirch *et al*, Phys. Rev. **A59**, p3375.

The agreement with experiment is pretty good, except for an excess below 1 keV where their detector loses efficiency.

Energy of Gammas from μ^- Boron (muMinusCaptureAtRest, QGSP_BERT_HP)
(Use Boron because I found a paper with its spectrum.)

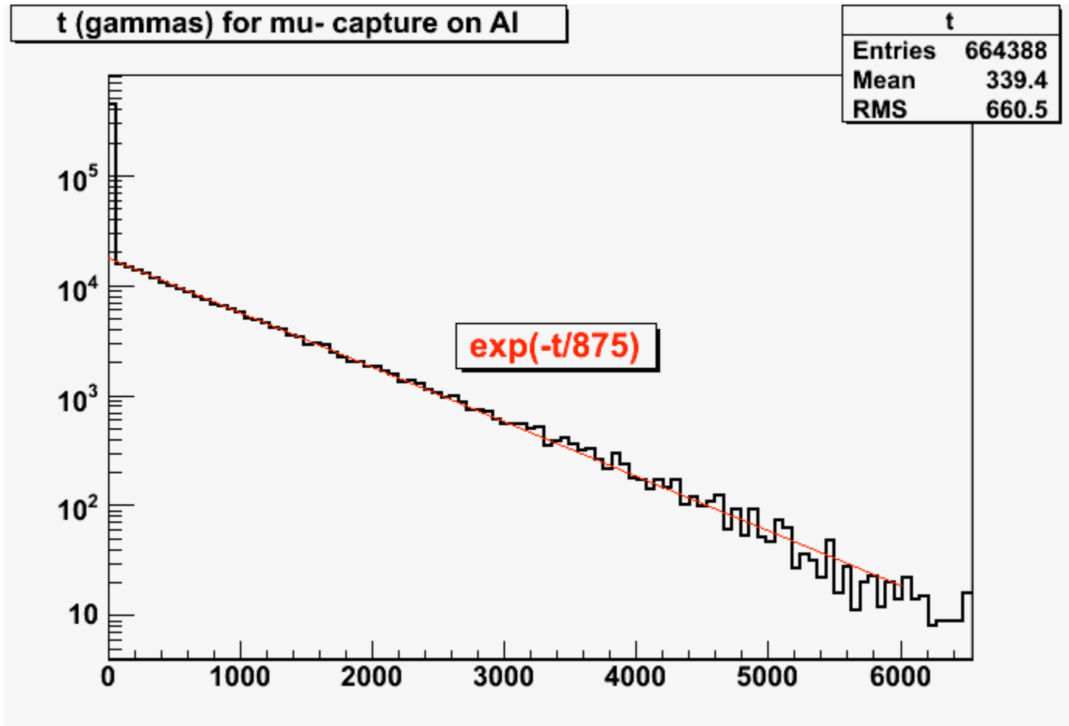




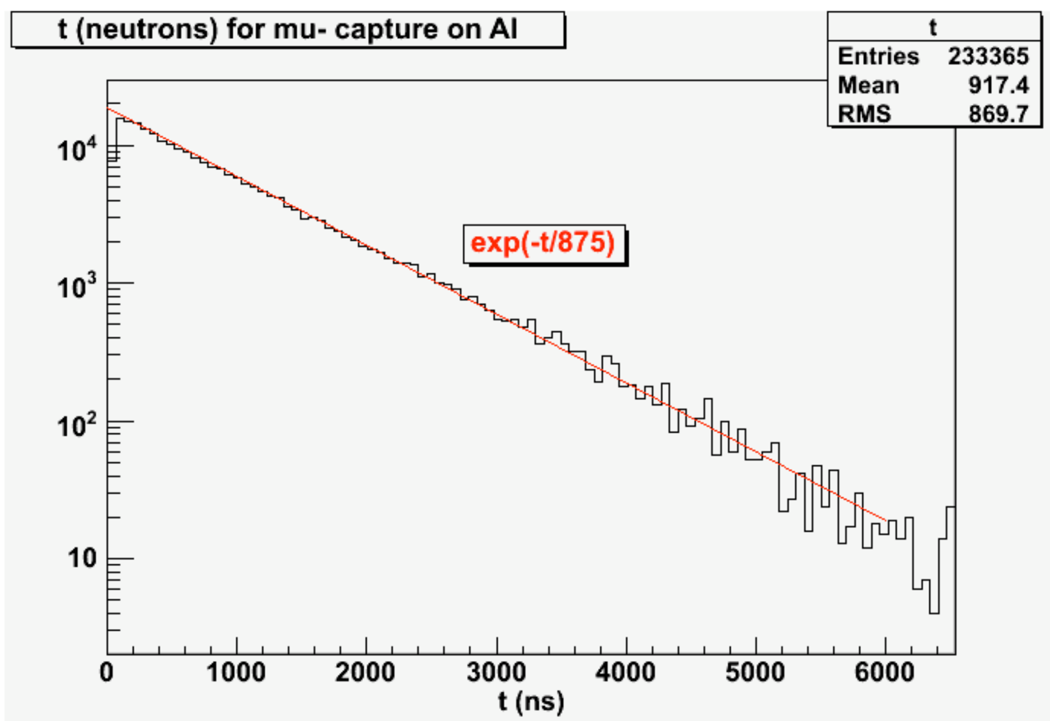
Experimental measurement of the Boron Lyman series, from Kirch *et al*.

There is reasonable agreement with experiment, except for a ~0.8 keV offset in energy calibration.

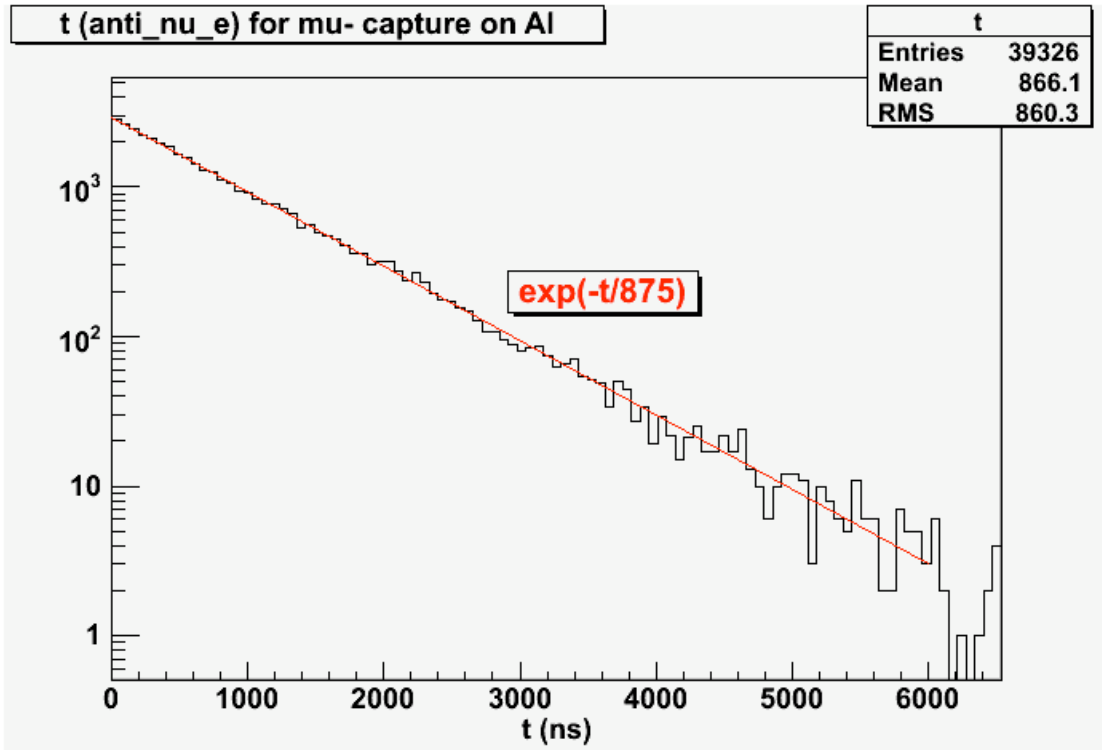
Time Plots



G4beamline time distribution for gammas. The prompt muon-atomic cascade is clear, as is the combination of nuclear capture and decay in orbit with a lifetime of 875 ns.



G4beamline time distribution for neutrons. These show nuclear captures, but there can be more than 1 neutron per event.

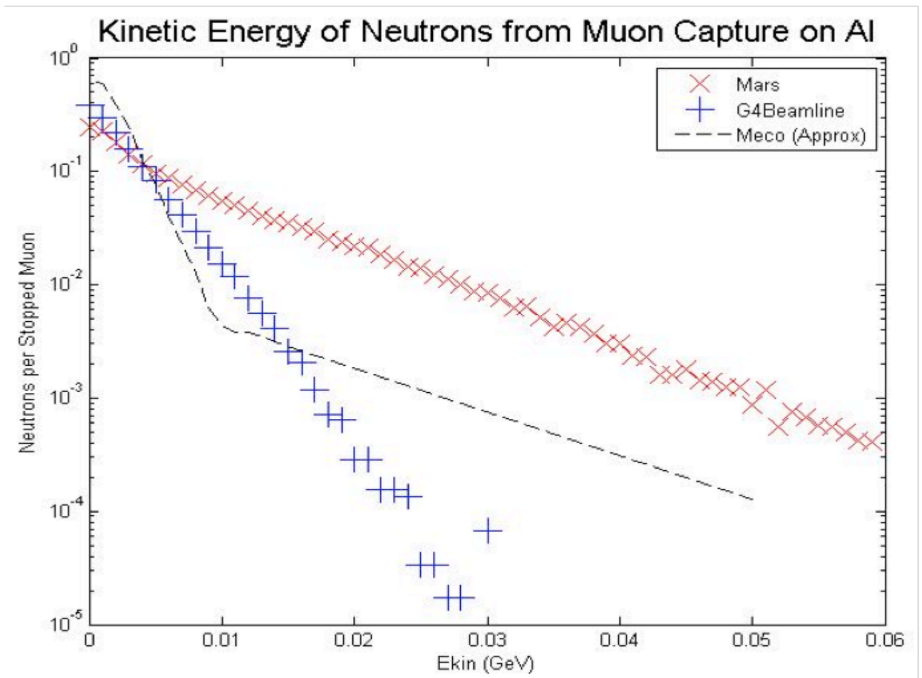


G4beamline time distribution for anti_nu_e. These are essentially all DIOs.

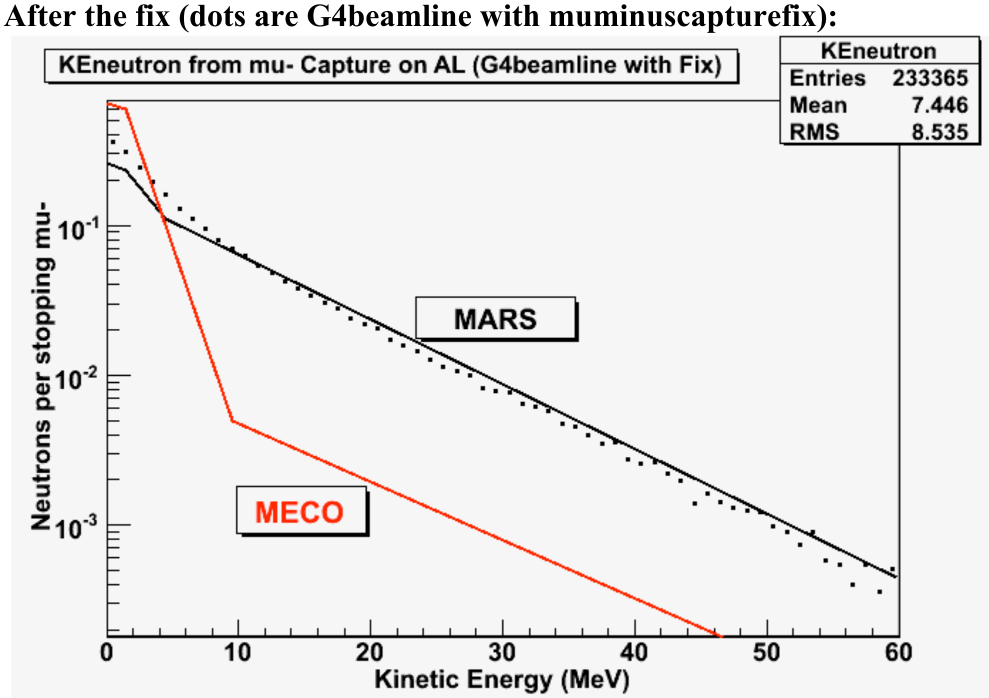
Neutrons

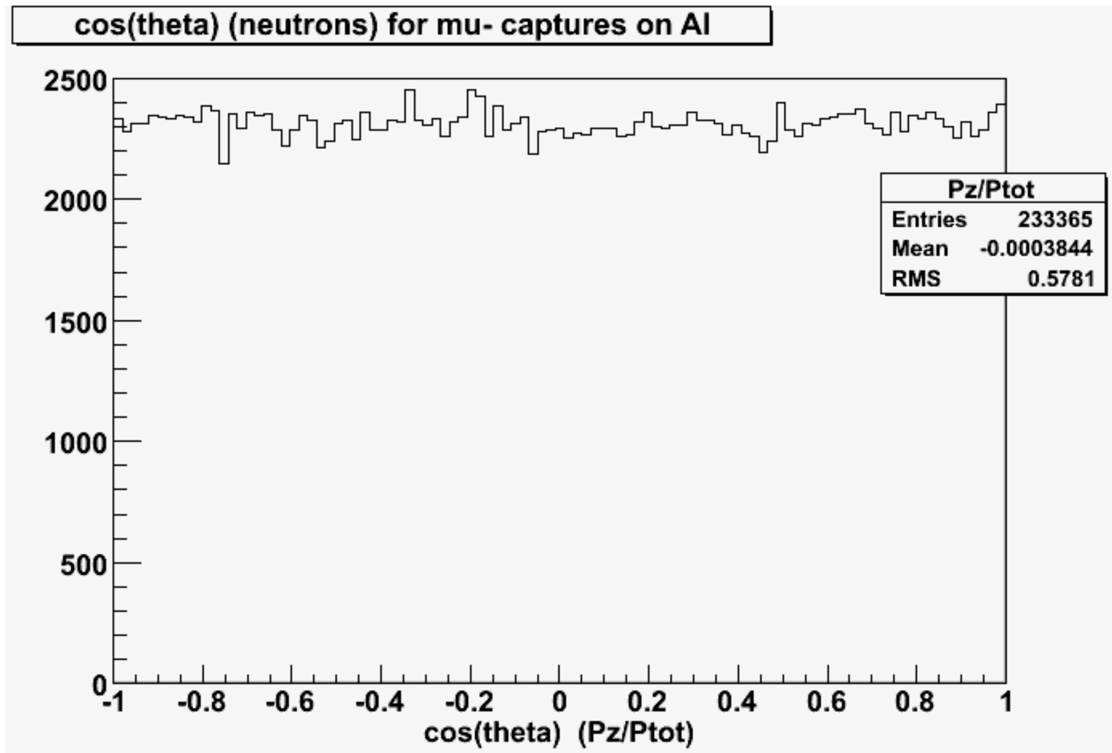
The muMinusCaptureAtRest process yields about 30% too few neutrons. As these are an important background, a fix has been implemented in G4beamline: the command “muminuscapturefix” will add additional neutrons to nuclear capture events (isotropically, with a distribution selected to match MARS, because we have no definitive experiment).

Before the fix:



After the fix (dots are G4beamline with muminuscapturefix):

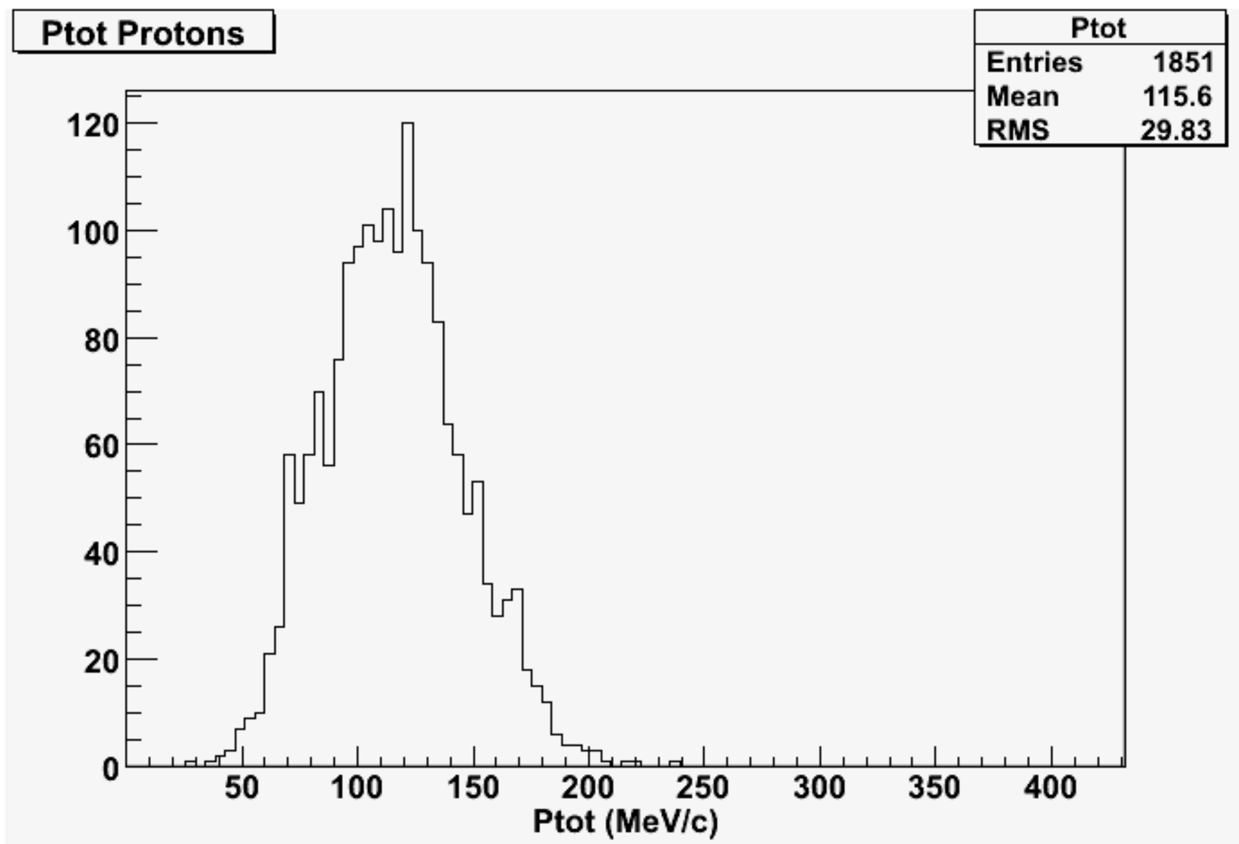




Angular dependence for neutrons.

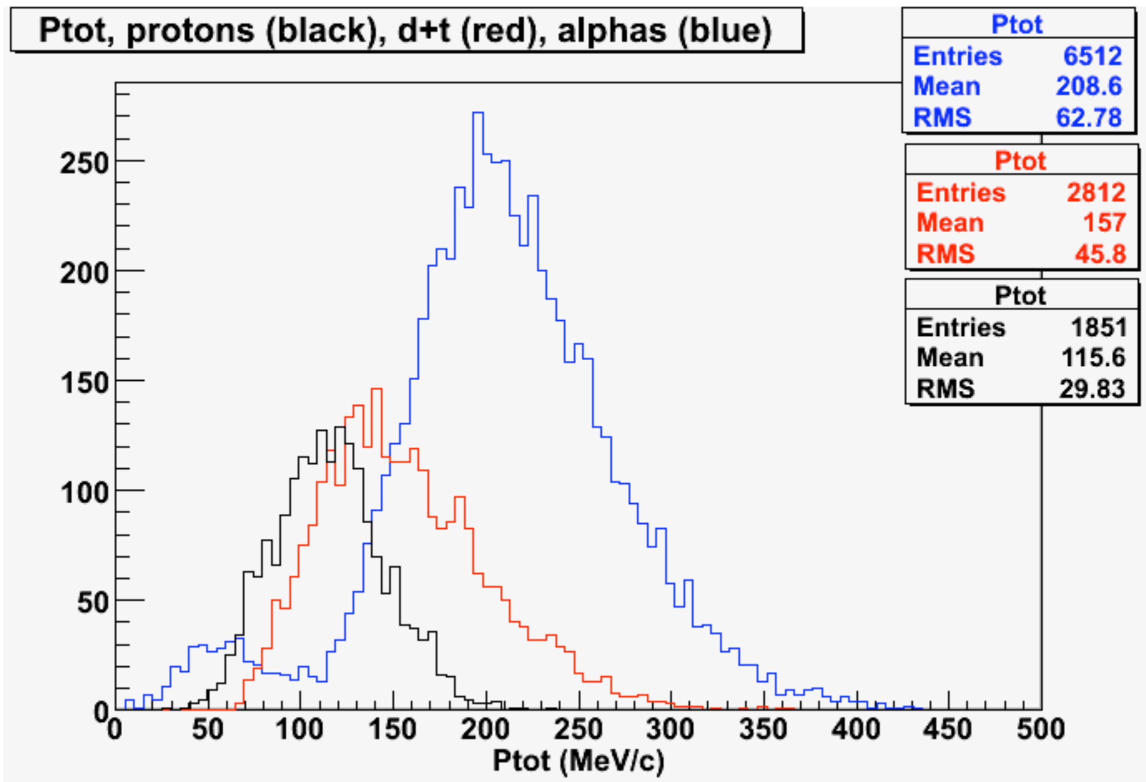
Protons

Protons from μ^- captures are a potentially serious background, as they could overload the tracker. Of course their charge is wrong so they are easily rejected after track fitting, but their rate is large enough to consider. Fortunately, all of the protons are below 250 MeV/c, and 12 mm of polyethylene will stop them all; 99.5% of them are below 200 MeV/c, and 6 mm of polyethylene will stop these. 2 mm of polyethylene will stop almost 90% of the protons. Note that these stopping values are for normal incidence, but for a proton to reach the Mu2E tracker it must have a large angle, which means they will stop in a correspondingly thinner sheet of polyethylene in the X-Y plane.



Other Particles

Neutrinos are produced by muMinusCaptureAtRest, but essentially all of them leave the detector. Nuclear recoils are also produced, but they rarely leave the target and are not a background in the Mu2E tracker. The only other particles not discussed above are alphas, deuterons and tritons[1]. They behave similar to protons, except for a given momentum they stop in even less polyethylene – 4 mm will stop 300 MeV/c deuterons, 600 MeV/c tritons, and 800 MeV/c alphas.



[1] For technical reasons, deuterons and tritons cannot be separated from each other in this plot; they are separated from all other particles.